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by William S. de Rosset and Jonathan S. Montgomery

ARL-RP-0491

July 2014

A reprint from *Wear*, Vol. 316, pp. 119–123, 14 May 2014.

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William S. de Rosset and Jonathan S. Montgomery
Weapons and Materials Research Directorate, ARL

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) July 2014		2. REPORT TYPE Reprint		3. DATES COVERED (From - To) October–November 2013	
4. TITLE AND SUBTITLE Cobalt-Base Alloy Gun Barrel Study				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) William S. de Rosset and Jonathan S. Montgomery				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-WMM-F Aberdeen Proving Ground, MD 21005-5069				8. PERFORMING ORGANIZATION REPORT NUMBER ARL-RP-0491	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES A reprint from <i>Wear</i> , Vol. 316, pp. 119–123, 14 May 2014.					
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15. SUBJECT TERMS cobalt-base alloy, muzzle wear, erosion, firing tests, wear pattern, gun tube liner material					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON William S. de Rosset
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) 410-306-0816



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William S. de Rosset*, Jonathan S. Montgomery

U.S. Army Research Laboratory, ATTN: RDRL-WMM-F, Aberdeen Proving Ground, MA 21005, USA



ARTICLE INFO

Article history:

Received 2 December 2013

Received in revised form

30 April 2014

Accepted 3 May 2014

Available online 14 May 2014

Keywords:

Cobalt-base alloy

Muzzle wear

Erosion

Firing tests

Wear pattern

Gun tube liner material

ABSTRACT

Firing tests of a small caliber experimental gun barrel made of a cobalt-base alloy have been conducted with the purpose of determining the degree of wear and erosion due to excessive firing durations. The small amount of barrel material loss makes the cobalt-base alloy an excellent candidate for use as a gun liner. An unusual wear pattern resulting from this loss was observed near the muzzle. Elimination of chemical and thermal effects made a plausible explanation of the wear pattern possible.

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1. Introduction

For over 50 years, the United States Army has used a short cobalt-chromium liner (Stellite 21^{®1}) in its M2 machine gun to reduce barrel wear and erosion. Even though this approach is highly successful, it has not been adopted for use in other fielded weapons. This may be due to the problems faced with emplacing the liner in the barrel or the perceived cost/benefit of the approach. Alternatively, chromium coatings have also proven to be effective in reducing wear. However, the plating process used to apply the chromium to the bore of the tube involves hexavalent chromium, a known carcinogen. This has led to efforts to find ways to replace the chromium plating process.

Recently, advances have been made in explosive bonding of liners to gun tubes [1–3] and in using a pressurization technique to attach the liner [4,5]. This has prompted considerable interest in alternate materials that might be used as liners. The United States Army Research Laboratory (ARL) was able to obtain several 5.56 mm barrels made entirely from a cobalt-chromium alloy. These experimental barrels served as a test bed to determine how this particular alloy would wear under extreme firing conditions. The intent of the firing tests was to demonstrate that a gun tube liner made of this material would extend the service life of the gun tube to the extent that the soldier would not have to carry a second barrel, as is now the case. The next section presents the

rationale and procedures for the firing tests as well as the equipment used to measure the bore diameter. The results section gives the experimental findings in terms of barrel wear as a function of shot number. An unusual wear pattern was observed, and this is discussed in the section following the results. Conclusions are presented in Section 5.

2. Materials and methods

The composition of the cobalt-base alloy (CBA) is presented in Table 1. The production of this alloy does not involve the use of hexavalent chromium. Consequently, the use of a liner made of this material would avoid that particular environmental issue.

Careful consideration was given to the firing cadence. In order to demonstrate the wear resistance of the CBA barrel, the plan was to test the barrels at increasing levels of firing durations. The baseline firing rate was that specified by the field manual appropriate for small caliber weapons [6]. The manual specifies two cadences: sustained and rapid. For sustained rate of fire, the manual calls for 3–5 round bursts, with 4–5 s between bursts. The barrel is changed every ten minutes. For rapid fire, the manual calls for 8–10 round bursts with 2–3 s between bursts, and the barrel must be changed every two minutes. The baseline cadence was denoted as the Phase 1 test. Thereafter, the firing tests were conducted with increasing durations. A separate barrel was used for each cadence. Barrel 1 was used for the sustained cadence, and Barrel 2 was used for the rapid cadence. Table 2 presents the complete firing sequence.

* Corresponding author. Tel.: +1 410 306 0816.

E-mail address: william.s.derossset.ctr@mail.mil (W.S. de Rosset).

¹ Stellite 21 is a registered trademark of Kennametal Stellite, Goshen, IN.

Table 1
Chemical composition of chromium-cobalt alloy.

Element	Co	Cr	Ni	Mo	Fe	W	Mn	Si	N	C
%	54	26	9	5	3	2	0.8	0.3	0.08	0.06

Table 2
Firing durations for two cadences.

Firing cadence	Phase 1 time (min)	Phase 2 time (min)	Phase 3 time (min)	Phase 4 time (min)	Phase 5 time (min)
Sustained	10	15	20	25	30
Rapid	2	3	4	5	6

After each firing phase was completed, the gun barrels were cleaned and their bore diameters measured with a laser system. The instrument used to do this was a Bore Erosion Measurement and Inspection System (BEMIS™) made by Laser Techniques Company (LTC) of Redmond, WA. The BEMIS allows bore diameter measurements along the entire barrel length and measures the bore diameter at both the land and groove positions.

Each barrel was placed in a standard machine gun. A pneumatic device was attached to the trigger and used to fire the weapon. The pneumatic device was controlled by a custom-made timing device that allowed two inputs: the time of firing, and the time interval between bursts. The trigger device was calibrated in initial tests that established the time of fire and intervals between bursts that would achieve the average rate of fire for both sustained and rapid cadences. The firing device allowed a uniform sequence of shots that might not have been possible with a gunner operating the weapon.

The ammunition was the standard $5.56 \times 45\text{-mm}^2$ M855 round, along with the M856 tracer round. These rounds are fired in a ratio of 4–1, respectively. This ammunition was selected as it is the most prevalent in the inventory and is well characterized.

After the tests were completed, Barrel 1 was sectioned along its length and the bore surface examined with a light microscope.

3. Results

The bore diameter measurements for Barrel 1 (sustained cadence) are shown in Fig. 1. The plots are keyed to the baseline and five phases, shows the accumulated bullet count. These measurements were performed at the land location. The measurements start near the origin of rifling, and the initial spike in the data is due to bore diameter variations prior to that point. The barrel length is 463 mm, including the chamber. In order to relate the axial position shown in Fig. 1 to the distance from the rear face of the tube (RFT), 30 mm must be added to the axial position. That is, 400 mm axial position corresponds to 430 mm from the RFT.

There is no discernible wear for the first 200 mm of bullet travel for all phases. Increased barrel diameter is observed starting at about 200 mm (axial position). The diameter goes through a peak at about 340 mm and then decreases. There is a sharp decrease in bore diameter observed for Phases 4 and 5 at around 250 mm. This is attributed to the effects of the gas port at this location.

Fig. 2 shows a micrograph of the bore surface for Barrel 1 at 10 mm from the muzzle. The surface is relatively smooth and is colored red. An energy dispersive spectrometry (EDS) scan of the surface is shown at 450 mm from the RFT shown in Fig. 3. The primary element on the surface of the bore is copper, coming from the bullet jacket. There are also trace amounts of cobalt and

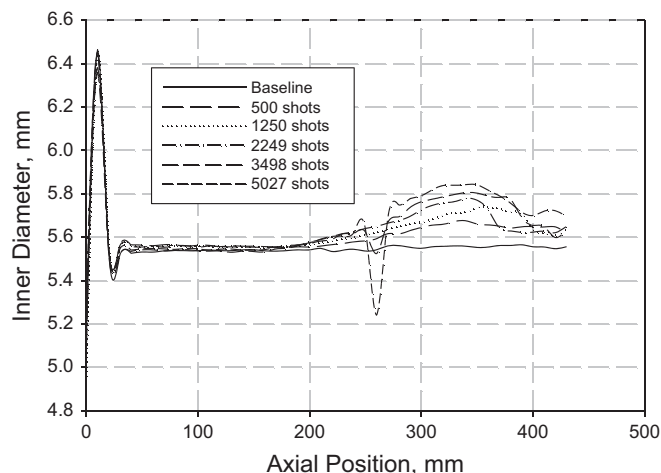


Fig. 1. Inner diameter as a function of axial position for Barrel 1.



Fig. 2. Bore surface of Barrel 1 at 450 mm from the RFT.

chromium. No metallurgical examination of the CBA was performed. However, no discernible cracks were observed in a micrograph of the CBA's cross section at 10 mm from the muzzle, as contrasted to the small cracks seen at 200 mm from the breech.

A sample of Barrel 1 was cut 6.5 mm from the end of the tube. The sample was mounted, polished, and observed under the eyepiece of a micro-hardness tester. The copper layer thickness varied from 0 to $15 \mu\text{m}$ ($0\text{--}1.5 \times 10^{-2} \text{ mm}$).

A micrograph of the surface 200 mm from the RFT is shown in Fig. 4. The dark lines at the upper and lower portion of the micrograph are the edges of the land. There appears to be a cross-hatch pattern of surface cracks in the CBA. Also, it appears that there are small deposits of copper on the edges of the land.

The bore diameter at the groove location for Barrel 1 begins to increase at about 290 mm. The exact location is obscured to some extent after Phases 4 and 5 by the anomalous behavior at the gas port location. Fig. 5 compares the measurements of the bore diameter at the land and groove positions taken after Phase 5.

Velocity measurements were performed during the tests of Barrel 1. The average muzzle velocity in each phase showed a 0.5% decrease for the 5027 shots. The average velocity in each phase for Barrel 2 showed a slight increase with phase number. In addition, yaw tests with Barrel 1 made after the Phase 4 tests indicated that the bullet yaw was very small.

Barrel 2 was fired at a higher rate than that for Barrel 1 but for a shorter period of time. As a result, fewer rounds were fired through Barrel 2. Inner diameter measurements at the land location are shown in Fig. 6. No discernible wear is observed for the first 200 mm of bullet travel. The bore diameter begins to increase at 200 mm axial position and then goes through a maximum at approximately 340 mm. The bore diameter decreases

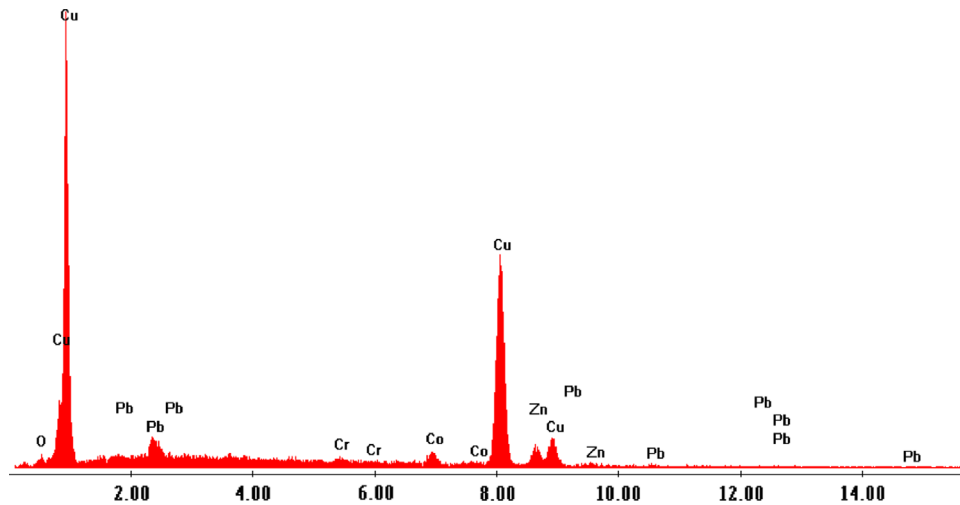


Fig. 3. EDS scan of the surface of Barrel 1 (450 mm from the RFT). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

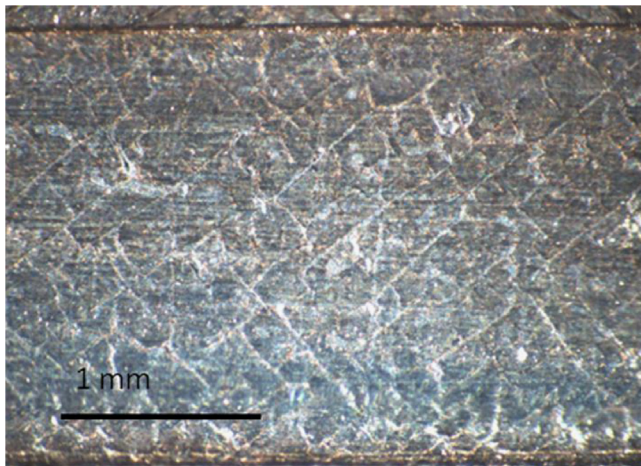


Fig. 4. Bore surface of Barrel 1 at 200 mm from the RFT.

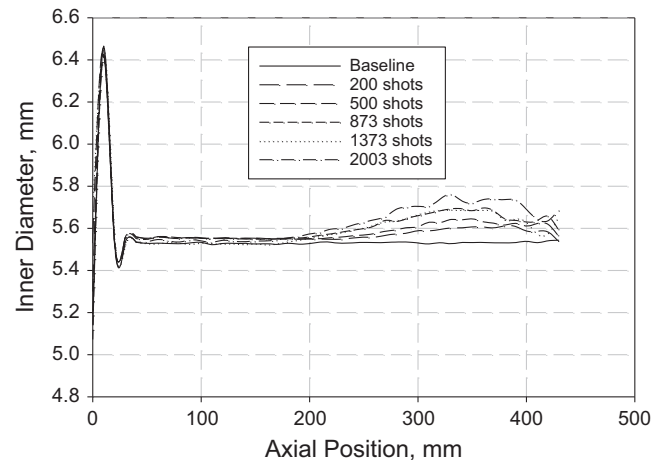


Fig. 6. Inner diameter as a function of axial position for Barrel 2.

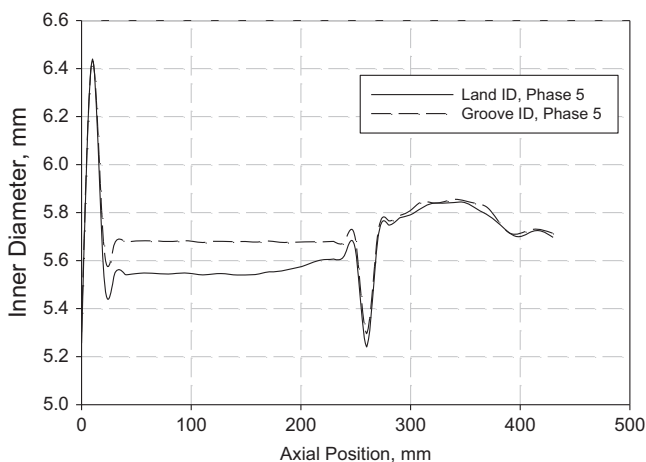


Fig. 5. Comparison of diameter measurements at the land and groove positions.

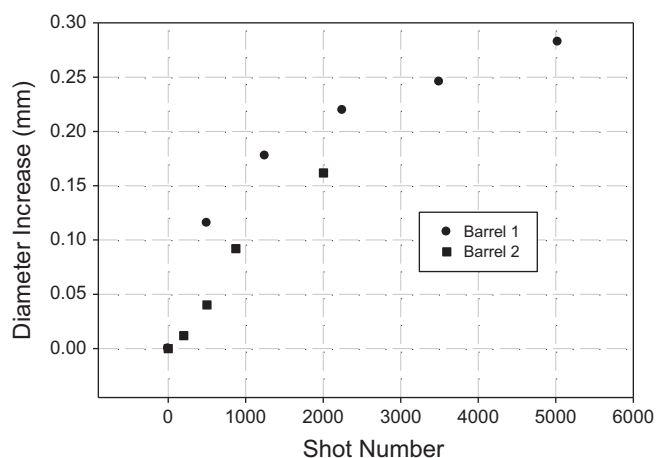


Fig. 7. Maximum barrel wear as a function of shot number.

near the muzzle in the same manner as observed with Barrel 1. The total number of shots was 2003. No anomalous decrease in the bore diameter was observed near the gas port for Barrel 2. Barrel 2 was not sectioned.

The maximum wear observed in both barrels does not appear to depend on the firing rate. Fig. 7 shows the maximum wear at

the land location for both barrels as a function of shot number. (This maximum did not always occur at 340 mm, but was generally close to this location.) Both barrels initially show a rapid increase in wear as a function of shot number. Barrel 2, which was fired at a higher rate than Barrel 1, does not show quite as much wear over the first 2000 shots. The rate of wear in Barrel 1 appears

to taper off for shot numbers greater than 3000. This may be due to the fact that the lands have worn away at this point (see Fig. 5) and further wear must occur for the entire surface of the bore.

4. Discussion

The terms “wear” and “erosion” are normally used in the context of gun barrel inner diameter increase due to firings. For purposes of this paper, we define wear as the loss of material predominantly due to the mechanical rubbing of the bullet against the bore. Erosion covers all other material loss mechanisms. The two are not always neatly separated. For instance, the propellant gasses may chemically attack the bore surface and soften it. When the bullet rubs against a surface that has been thus weakened, material removal is enhanced. Similarly, if the bore surface is heated to such a degree that a thin liquid metal coating is formed, the coating may be easily removed by the bullet wiping it off. To complicate matters, there may be combined thermal and chemical effects.

Use of the CBA as a barrel material has allowed, to a great degree, the separation of wear and erosion. In particular, such alloys are resistant to high temperatures and chemical attack. Therefore, one might expect that mechanical wear will be the primary cause of material loss.

Mechanical wear at the muzzle has been routinely observed in cannons [7]. It is restricted to reduction in the land height due to sliding of the projectile against the land surface. It is enhanced when the steel projectile body, rather than the copper rotating band, contacts the lands. Muzzle wear in small caliber weapons is also prevalent, and there are gages available to measure it (see, for instance, Fulton Armory part number FA-A277-CGMST). There have not been extensive studies on the cause of muzzle wear in small caliber weapons, but it is conjectured that the causes of this wear are probably similar to those in larger caliber bores. This can include projectile unbalance, obturation failure, and cocking of the projectile in the bore [8]. In particular, the bullet may be manufactured such that the center of mass does not lie on the axis of the projectile. As it spins down the barrel, there would be centrifugal forces that increase with bullet velocity, causing transverse pressure on the bore. This would lead to an increase in bore diameter as a function of axial position down the bore. The standard gage is designed assuming this bore diameter increases monotonically near the muzzle.

The standard gage would not work with the CBA barrel. The bore diameter does not continue to expand with distance from the breech. Rather, it goes through a maximum at about 100 mm from the muzzle and then decreases to a value slightly larger than the bore diameter at the muzzle, depending on shot number.

There has been some modeling work addressing muzzle wear in cannons. This work involves large caliber weapons, so the transfer of results may not necessarily apply to small arms. For instance, Andrade et al. [9] have conducted a numerical study on gas blow-by for a large caliber cannon. They considered two gap sizes between projectile and gun tube wall. Gas flow past one side of the projectile forced the projectile to travel with its axis not aligned to the gun tube axis, also known as balloting. Muzzle wear was attributed to this balloting. In addition, these authors found that the heat transfer rate to the gun tube wall at the blow-by location could be several orders of magnitude higher than nearby rates.

A detailed analytical or finite element modeling of the wear and erosion processes was not in the scope of the present work. However, a qualitative explanation, consistent with the observations and known interior ballistic phenomena, can be offered. The possibility of competing effects was first examined. The bore

diameter begins to increase at approximately 230 mm from the RFT (200 mm axial position in Figs. 1 and 5), which suggests that there is a critical velocity (or spin rate) necessary to begin material removal from the bore. At 360 mm from the RFT, the rate of material removal begins to decrease. One possible explanation involves the hot hardness of the CBA. The bore surface temperature decreases as a function of axial position. This will lead to an increase in the surface hardness of the CBA, making material removal more difficult. However, it is unlikely that the temperature gradient down the gun tube is large enough to give the observed effect. In addition, the starting point of the material loss tends to move toward the breech as the number of shots increases. This observation argues against a fixed critical velocity needed to begin the process.

If anything, the low surface hardness of the CBA material near the breech should enhance whatever wear might occur. The fact that no measureable material removal was observed for the first 200 mm of bullet travel (past the origin of rifling) is critical to elucidating the wear process for this material. There are three different wear phenomena that come into play near the breech. The first is the possibility that the bullet enters the bore in a cocked position. This would lead to an imbalance of forces on the bore of the tube and increased wear on one side. The second phenomenon is the engraving forces at the beginning of bullet travel. These are large enough to deform the copper. Finally, the initial pressure spike provided by the burning propellant will cause the bullet to expand due to the Poisson effect. This will result in pressure of the bullet against the bore surface. (The tube also expands behind the bullet, but not enough to produce a loss in obturation.) These three phenomena, combined with the lower surface hardness of the CBA, might be expected to result in material removal near the breech end of the tube.

The observation of no wear for the first 200 mm of bullet travel raised the possibility that the observed loss of material downbore was not due to contact between bullet and bore surface. That is, if the CBA could resist wear where it was expected, then it might be possible that this material would not wear at all by the action of the rubbing surfaces.

This line of thought led to the following hypothesis. During the initial portion of bullet travel, the high pressure behind the bullet causes the bullet to expand and contributes to the obturation of the bullet. At approximately 200 mm of bullet travel, the pressure behind the bullet has decreased to the point where this contribution becomes small, and hot propellant gas and particulate matter from unburnt (or burnt) propellant blow by the bullet. This gas wash, as it is called, is the source of material loss. It occurs only for a short time, at which point the pressure has been lowered to the point where the gas and particulate matter can no longer get past the bullet. This explanation puts the material loss process into the erosion category.

This is a qualitative explanation and is not supported by any modeling. However, it is consistent with many of the observations. First, it provides a logical explanation for the start of the erosion process without invoking a critical bullet velocity. It is consistent with the observation that there is no gradual increase in material loss from the start of bullet travel. In addition, it would also explain the apparent creep of the start of the process towards the breech for erosion at the land location. The earlier start of the erosion process is simply due to the fact that as the barrel loses material at about 200 mm of travel, the propensity of gas blow-by increases at a point closer to the breech. The erosion process starts later at the groove location. The engraving process, as well as the lateral forces applied to the land wall, may make the lands weaker than the grooves, causing earlier erosion at the land location.

The explanation also accounts for the maximum in the erosion in a natural way. That is, once the gas pressure is relieved, the

erosion process ceases. The fact that the bullet goes past the gas port also will decrease the pressure.

Copper deposits were observed to start at about 30 mm from the muzzle and increased in intensity so that the last 8 mm were fully coated. Given the fact that no such copper deposits were observed near the breech end of the gun tube, the copper deposits must be due to the gas wash and particulate matter removing jacket material. The copper was then deposited on the gun tube wall. The copper deposit will contribute to the decrease in the measured bore diameter. However, the measured thickness ($0\text{--}1.5 \times 10^{-2}$ mm microns) was too small to account for the decrease in diameter at the muzzle ($\sim 1.5 \times 10^{-1}$ mm).

5. Conclusions

The original goal of this work was to demonstrate that the particular CBA used as a gun liner material would allow a soldier to fire a weapon without worrying about rate or duration of fire. Barrel 1 made entirely of CBA survived an abusive firing schedule and was still properly functioning after more than 5000 rounds at the sustained rate of fire. The same can be said about Barrel 2 at the rapid rate of fire at 2000 rounds. Loss of barrel material was minimal and confined to a small region near the muzzle. This material loss did not degrade the performance of the weapon to any great extent. Consequently, this particular CBA is a prime candidate for use as a gun liner material.

During the firing tests, an unusual wear pattern was observed in which the loss of gun barrel material went through a maximum near the muzzle end of the barrel. A plausible explanation, consistent with the observations, was made that involved gas blow-by. Additional analytic modeling and basic material characterization need to be conducted to confirm or deny this hypothesis.

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Acknowledgments

The authors thank the U.S. Army Research Laboratory for sponsoring this work. We are indebted to George Gibbs (USMC) and the Small Business Innovative Research Program for the cobalt-based alloy barrels. We also wish to acknowledge the BEMIS measurements by Robert Keppinger, the microscopy/EDS work by Bradley Klotz, and the sample mounting and polishing by James Catalano.

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